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SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2001-170**
G.G. Spanjers, "New Satellite Propulsion System has Mass Below 100 Grams (0.22 lbs.)"

Horizons Article **(Statement A)**
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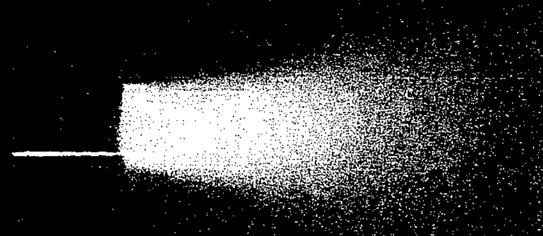

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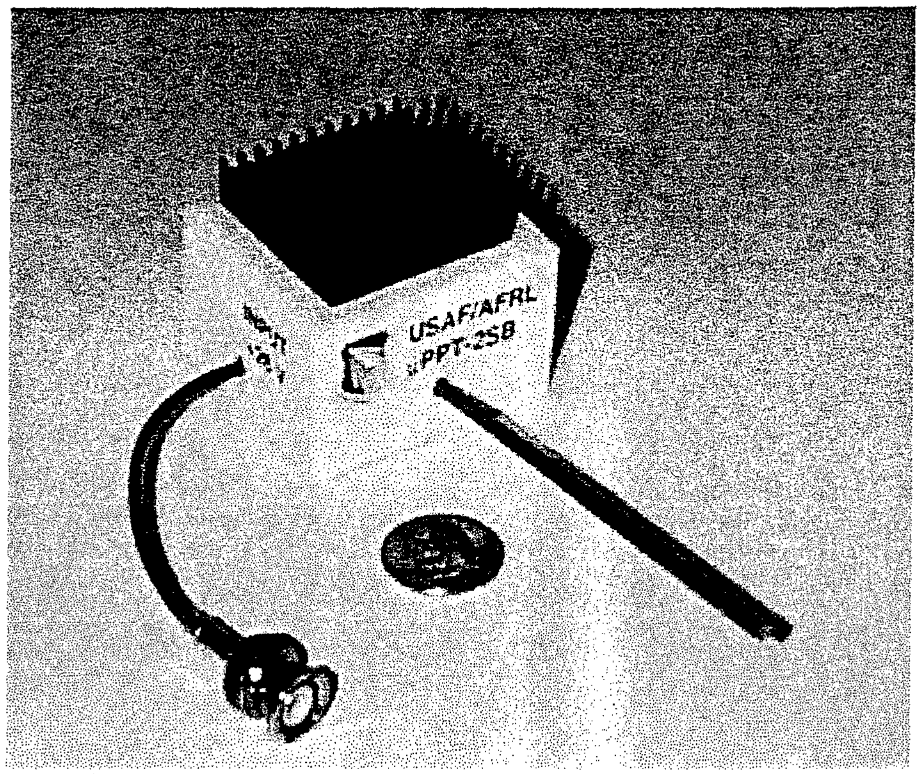

Figure 1 Photograph of a MicroPPT prototype next to a quarter for size comparison. The propulsion system requires only a 28V input from the spacecraft power bus and has a total mass of 100 grams.

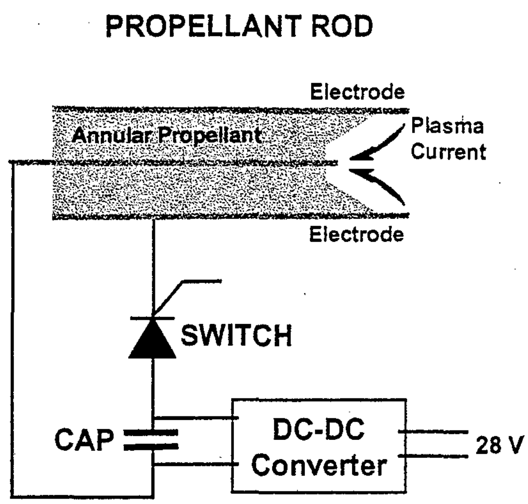

Figure 2. Example electrical schematic of a MicroPPT

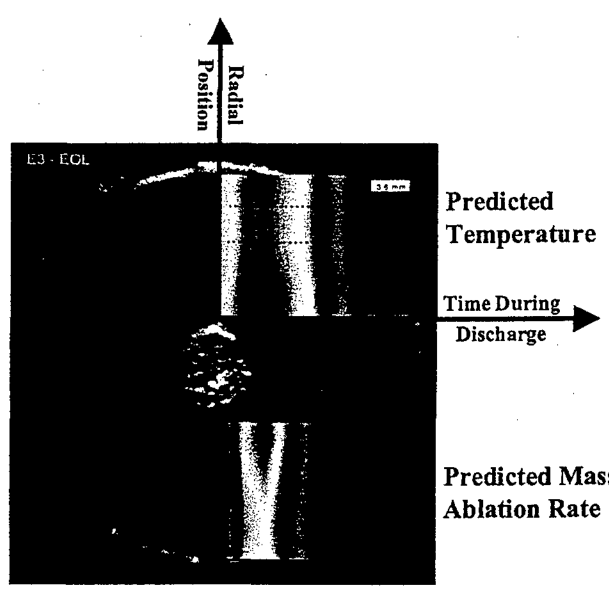

Figure 3. Contour plot of the predicted propellant temperature and mass ablation rate, superimposed on a photograph of a MicroPPT with char formations. Red corresponds to the highest temperatures and blue corresponds to the coolest temperatures. A qualitative agreement is apparent between the radial locations of the minimum temperature, minimum mass ablation rate, and the observed char formation.

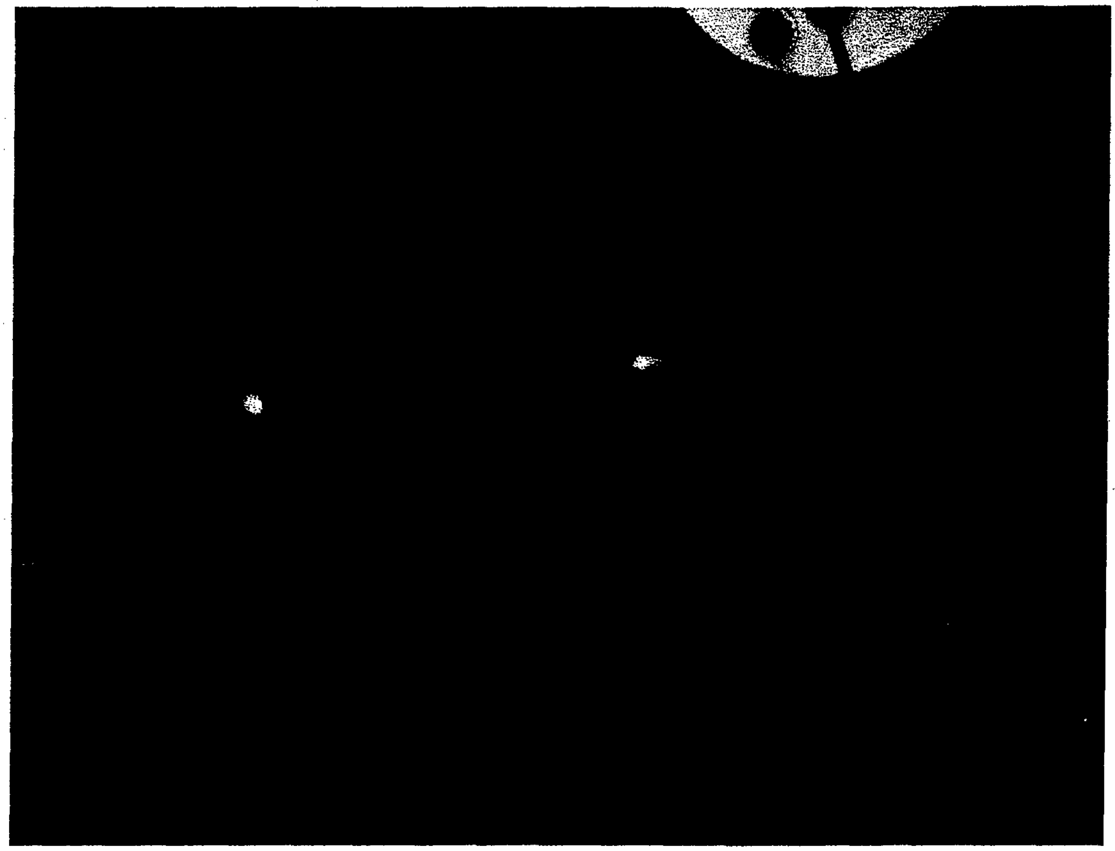

Fig. 4 MicroPPT firing with almost all of the available propellant expended. The copper tube extending to the right is the propellant assembly. The discharge is occurring within the tube, approximately ¼" from the left end. The blue plume to the right is the plasma exhaust from the MicroPPT. The red light visible to the left is light from the discharge arc, transmitted through the ¼" of remaining propellant and visible out the back of the thruster.

Title: New Satellite Propulsion System has Mass below 100 Grams (0.22 lbs)

Subtitle: Miniaturized propulsion systems are a critical technology for a new class of Air Force micro-satellites performing highly specialized missions.

Source: AFRL's Propulsion Directorate, Space and Missile Propulsion Division, Spacecraft Branch, Edwards AFB, CA.

Submitter: This article was written by Dr. Greg Spanjers of the Air Force Research Laboratory's Propulsion Directorate. For further information contact TECH CONNECT at 1-800-203-6451 or visit the web site at http://www.afrl.af.mil (Technology Transfer).

Introduction: There is an increased requirement for propulsive microsatellites to support a range of future specialized Air Force and NASA missions. Once the micropropulsion technology is developed, fleets of microsatellites acting in concert will have the maneuverability needed to form sparse-aperture radar arrays in orbit. Similar microsatellite formations directed toward space will search for far-away planets or detect gravity waves. Individual microsatellites will be used to approach and inspect damaged satellites. Specialized microsatellites can then be deployed to enact repairs, upgrade electronics, or refill propellant tanks. Propulsion systems that provide precise impulse bits in the 10 micro-Newton range are an enabling technology for a new fleet of 25-kg class spacecraft envisioned for these missions. In response to this need, the Propulsion Directorate is developing miniaturized propulsion systems weighing about 100 grams.

Supplemental Information: The Micro Pulsed Plasma Thruster (MicroPPT)[1] is a simple, miniaturized propulsion device designed for propulsive attitude control on present 100-kg small satellites, and for stationkeeping and primary propulsion on next-generation 25-kg class microsatellites. The primary attractive features are the use of a solid inert propellant (Teflon™), expected high-I_{sp} due to the use of electromagnetic acceleration, and a simple, lightweight design based largely on commercial, flight-qualified electronic components. For 100-kg class small satellites a set of 4 MicroPPTs, each designed with 3 selectable thrust directions, can provide full spacecraft attitude control, yet require only 1/10th the mass of standard torque rods and reaction wheels.[2] The MicroPPT was invented in 1997 at the AFRL Spacecraft Propulsion Laboratory at Edwards AFB. It is currently manifested for flight as a micropropulsion demonstration aboard the AFRL TechSat21, scheduled for launch in 2004. The rapid advancement of the MicroPPT from invention to flight manifestation is indicative of the inherent simplicity of the device, and also indicative of the importance AFRL is currently placing on the development of microsatellite enabling technologies.

The MicroPPT, shown in the photograph of Figure 1, uses a solid Teflon™ propellant, which aids the miniaturization by eliminating the need for the propellant tanks and valves associated with traditional gaseous and liquid propellants. The propellant assembly is fabricated in a coaxial geometry with an inner conductive rod for the cathode, surrounded by an annulus of non-conductive propellant, and an outer conductive shell for the anode. Firing the MicroPPT requires a simple electronic circuit, such as the design[3] shown in Figure 2. A DC-DC converter charges the small capacitor to about 3000 volts, depending on the geometry of the propellant assembly

being used. Closing the switch applies the voltage to the MicroPPT electrodes and across the propellant face. With properly chosen electronics and propellant geometry, the pulsed voltage will exceed the surface breakdown strength at the propellant face. A surface discharge arc forms and acts to heat, vaporize, and partially ionize the solid propellant. The ionized propellant is then accelerated by a combination of thermal and electromagnetic forces to create usable thrust.

Over the satellite lifetime, the electrodes can be designed to ablate away with the propellant, or by increasing the thickness of the outer anode, to ablate only the inner cathode leaving an empty tubular shell.[4] In either design, the propellant initially possesses reasonable rigidity, which decreases during the mission as the propellant and electrodes are consumed. This makes the MicroPPT an attractive propulsion option for self-consuming satellite designs. The propellant modules would be designed to serve as satellite structural elements during the high vibration environment of launch. Once in orbit, where the structural requirements are greatly reduced, these same modules are consumed as thruster propellant. The payoff is a mass savings for the spacecraft.

The MicroPPT has some heritage in devices used as plasma sources, most notably the cable guns used in plasma opening switches.[5] Cable guns use a surface discharge and the same coaxial geometry, although with diameters a factor 2 to 4 times larger and a graphite coating applied to the Teflon™ insulator face to act as the material source for the plasma. After about 20 discharges, the cable-gun coating has to be reapplied to avoid insulator (Teflon™) erosion and erratic operation. Cable guns are generally energized using high voltage capacitor banks (0.6 μF, 25kV, 188J) and switched using spark gaps. Working from the cable gun heritage, the AFRL design goals for the MicroPPT have been to:

- Directly use the Teflon™ insulator as the ablative material, since reapplying a graphite coating is impractical for space applications.
- Reduce the capacitor voltage by a factor of 5 to 10, to the 3000 – 8000 V range.
- Replace or eliminate the spark gap switch since it is unlikely to meet flight qualification requirements.
- Reduce the discharge energy about 100 times, to the range of 1 – 10 J.
- Increase the usable lifetime from 20 discharges to over 1 million discharges.

research and [illegible] of [illegible]

Over the past 3 years the MicroPPT has undergone extensive research development at AFRL. The design strategy has been to use commercial off the shelf sources (COTS) for the electronic components, and then focus the AFRL research on designing propellant assemblies compatible with the COTS electronics. Testing has shown that the critical parameters are the propellant surface area and the capacitor discharge energy. If the energy/area ratio is too high, the electronics mass will be excessive, and temperature effects will increase the propellant mass consumption rate.[6] If the energy/area ratio is too low, the propellant will exhibit the formation o a char layer on the surface. This char layer will increase the surface breakdown voltage, and is considered a failure mode for the thruster. To aid in the understanding of the char formation, AFRL is working with the University of Michigan to develop a basic physics relation between the propellant temperature during the discharge and the char formation.[7] The discharge current and plasma distribution are modeled in order to simulate the convective heat transfer back to the propellant face. This heat flux is then used to predict the Teflon™ surface temperatures and local mass ablation rate. In Fig. 3, where the predictions are compared to the char formation

ıentally, it is apparent that the regions of decreased propellant temperature and e correspond to the regions of char formation. This qualitative agreement that attribute char formation to incomplete decomposition and vaporization of er at reduced temperatures.

:ory testing, coupled with modeling and analysis, has led to MicroPPT ɔly designs that reproducibly demonstrate long lifetimes without char ›PPT lifetime is now limited only by the amount of available propellant and has trated over 1 million discharges without failure. A graphic example is shown in hows a photograph of a MicroPPT firing with almost all of the propellant ischarge is occurring within the tube, approximately ¼" from the left end. The right is the plasma exhaust from the MicroPPT. The red light visible to the left lischarge arc, transmitted through the ¼" of remaining propellant and visible ıe thruster.

forts on the MicroPPT range from basic research to advanced engineering comparatively simple version of the MicroPPT is undergoing flight engineering for demonstration aboard the AFRL TechSat21 flight,[8] scheduled for launch in ınced laboratory models have demonstrated several features critical for future

vith system dry masses as low as 60 grams.
hat increase propellant throughput by using a 10 times larger propellant area, ye ss voltage to initiate the discharge.
hat increase propellant throughput by bundling several propellant assemblies n a cluster. When the propellant from one assembly has been expended, the automatically changes to the neighboring propellant assembly without the use :ra electrical components.
hat select and fire different propellant assemblies from a single electronics This is the basis for a propulsive attitude control system, where the propellant s would be aligned with different thrust vectors.

L MicroPPT development effort is to use a combination of ground and flight ıtrate a thruster with at least a 500% improvement over state-of-the-art in terms lelivered normalized to the thruster wet mass. If successful, the program will ıe Phase II goals for Electromagnetic Spacecraft Propulsion under the AFRL torate IHPRPT program. The payoff of the effort will be enabling propulsion s, and an immediate 90% reduction in ACS mass for existing small satellites.

Spell out (ACS) more
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[4] Gregory G. Spanjers, US Provisional patent application No. 60/097,034 filed 17Aug98. titled "Micro-Pulsed Plasma Thruster Having Coaxial Cable Segment Propellant Modules"

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